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A SINGLE PULSE SUB-NANOSECOND PROTON RFQ

R. W. Hamm[1], H. Pearce-Percy[2], D. Pearson[2], M. Rougieri[2], J. Weir[2], A. Zografos[2], G. Guethlein[3], S. Falabella[3], S. Hawkins[3], B. Poole[3], and D. Blackfield[3]

[1]*R & M Technical Enterprises, Inc., Pleasanton, CA*
[2]*Compact Particle Acceleration Corporation, Livermore, CA*
[3]*Lawrence Livermore National Laboratory, Livermore, CA*

A Radio Frequency Quadrupole (RFQ) linac system has been developed to provide a single pulse of 2 MeV protons with a beam pulse width of ~300 ps and a charge of 30 pC, either for injection into a pulsed Dielectric Wall Accelerator or for bombardment of a target to produce a fast neutron pulse. The 1.2 m long RFQ structure operates at 425 MHz and bunches and accelerates a single 2.35 ns beam pulse injected into it at 35 keV using a parallel plate deflector placed directly in front of the RFQ entrance. The input acceptance properties of the RFQ allow a simple dc bias voltage on the plates to block acceleration of the unwanted beam, with a short rf voltage pulse applied to null the deflection field for the ions within the 8 mm "kicker" plate length. The use of the RFQ as the accelerating structure allows one to efficiently produce a large charge in a single sub-ns bunch. In addition, the kicker can also be used without the dc bias voltage to produce a "notch" in the normal RFQ output beam for synchrotron injection.

I. INTRODUCTION

The Compact Particle Acceleration Corporation (CPAC), in collaboration with Lawrence Livermore National Laboratory (LLNL), is developing a proton therapy system based on the high gradient Dielectric Wall Accelerator (DWA) structure,[1] with the demonstration of a prototype DWA structure currently underway. A spark hydrogen ion source and a 1 MeV induction linac structure had been under development at LLNL as the injector for the DWA.[2] However, the spark ion source appeared to have an unacceptable lifetime for use in a proton therapy system, so an alternate solution using a plasma ion source and a "bunching" accelerator structure was sought. In addition, recent beam dynamics simulations of the DWA indicate that an injected beam energy >1 MeV is desirable for achieving optimum performance of the DWA. Since the Radio Frequency Quadrupole (RFQ) structure is the best "bunching" accelerator available for low energy protons,[3] the design and fabrication of a 2 MeV RFQ accelerator was completed and the system has now been successfully demonstrated as an injector for the DWA.

The recent beam dynamics studies of the DWA structure and the beam requirements for proton therapy dictate the requirements of the DWA input beam as follows:[4]

- H^+ ion beam with energy greater than 1 MeV.
- Single pulse with width <300 ps.
- Beam radius <3 mm with total normalized emittance <8 mm-mrad.
- Beam repetition rate variable from single shot to 10 Hz, with charge per pulse from 3 to ~30 pC.

In addition, it is desirable that the injector be compact for use with the DWA in a proton therapy system.

At an rf operating frequency of 425 MHz, the RFQ cavity has a Q of ~7000 with a cavity fill time of ~10 µsec. Hence, the cavity is usually pulsed with an rf pulse width of 15 to ~1000 µsec. This timing structure then provides an output beam "macropulse" width from 5 to 1000 µsec as indicated in Fig. 1. Within each macropulse the beam has the frequency structure of the cavity (425 MHz) and within each rf cycle the output beam "micropulse" has a time structure of a fraction of the rf cycle, depending on the final rf phase width of the beam at the exit of the structure. The microstructure shown in Fig. 1 is typically for an RFQ operating at a resonant frequency of 425 MHz.

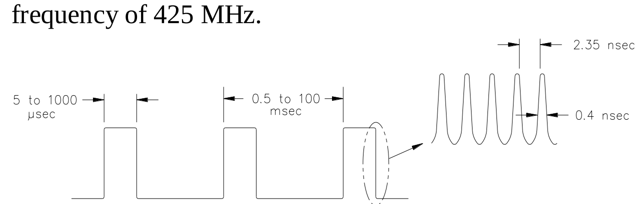

Fig. 1. DWA Injector RFQ beam timing.

An RFQ linac typically captures >80% of a dc proton beam injected into it at an energy of a few 10's of keV, and at a resonant frequency of 425 MHz, usually provides bunched micropulses of ~0.40 nsec width with an energy spread of ±1%. However, the flexibility of the RFQ design process allows one to make trade-offs among the various design parameters (such as beam modulation, relative phase, longitudinal emittance and transmission) to achieve different output beam properties. For the present case, this trade-off was used to provide a shorter beam micropulse for injection into the DWA.

Only a single micropulse from the RFQ is required for injection into the DWA. This can be accomplished using a beam deflector ("kicker") at the entrance to the RFQ so that only a single rf cycle (2.35 ns) is filled and bunched as it is accelerated. The rise and fall time of the deflected pulse must be as short as possible to insure that the beam injected into the RFQ completely fills one rf cycle, while minimizing the charge in the adjacent cycles.

II. RFQ DESIGN

The operating parameters for the proton RFQ linac designed as an injector for the DWA are listed in Table I. This 1.2 m long RFQ accelerates a beam of protons extracted at 35 keV from a duoplasmatron ion source to 2 MeV. The current limit of the design is more than twice the output current required for the DWA, giving ample margin for the structure's performance.

TABLE I. DWA Injector RFQ Linac Parameters.

Parameter	Value	
Operating frequency	425	MHz
Injection energy	0.035	MeV
Final beam energy	2.0	MeV
Design input current	50	mA
Current limit	80	mA
Transmission at 50 mA (%)	79	%
Input transverse emittance (norm)	0.3	π mm-mrad
Nominal vane voltage	88	kV
Bore radius	2.54	mm
Maximum vane modulation	2.2	
Structure length	1.16	m
Peak RF field surface gradient	45.6	MV/m
Pulsed structure power	175	kW
Pulsed beam power	80	kW

The design parameters of the RFQ vanes are shown as a function of the cell number in Fig. 2. The standard RFQ design first developed at Los Alamos National Laboratory was used for this system. The vane voltage is constant along its length and the vane tips radius is constant. However, to reduce the output phase width of the beam, the vane modulation (m) and synchronous phase (φ) are ramped even in the acceleration section.

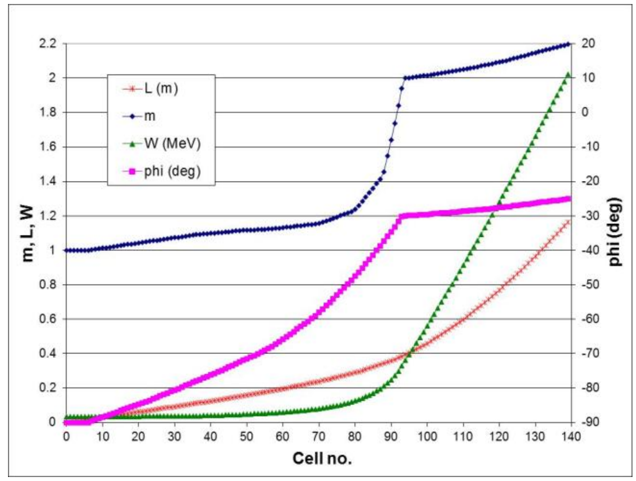

Fig. 2. RFQ design parameters for DWA Injector Linac.

The calculated phase space projections of the particles at the output of the RFQ using 50 000 macroparticles[5] in PARMULT, are shown in Fig. 3. The total phase width of the beam represents a time width of 315 psec, but 90% of the charge is within 210 psec. Figure 4 shows the output emittance in all three planes, with the beam in the transverse planes exiting the RFQ almost as a circular beam with a waist of 2 mm diameter. Figure 5 shows the beam transmission and longitudinal emittance of the RFQ calculated as a function of the intervane voltage. These calculations clearly show that the variation in transmission and longitudinal emittance is small above the design vane voltage, indicating that the RFQ output beam will have a high level of current and energy spread stability with respect to small variations in the input rf power. Hence, the beam from the RFQ meets the input requirements for the DWA structure.

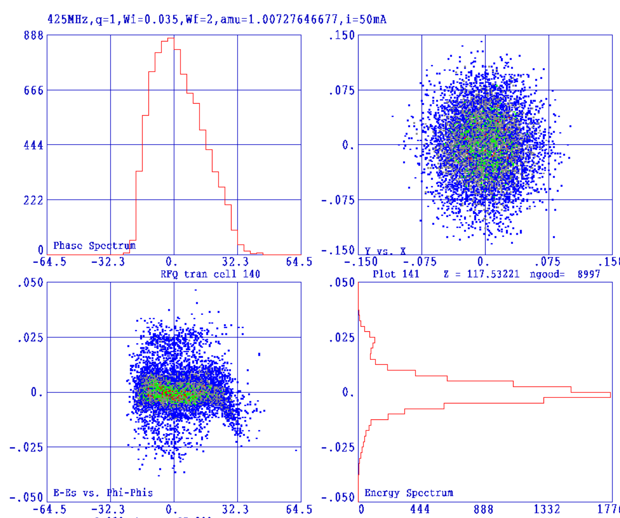
Fig. 3. RFQ output phase space projections.

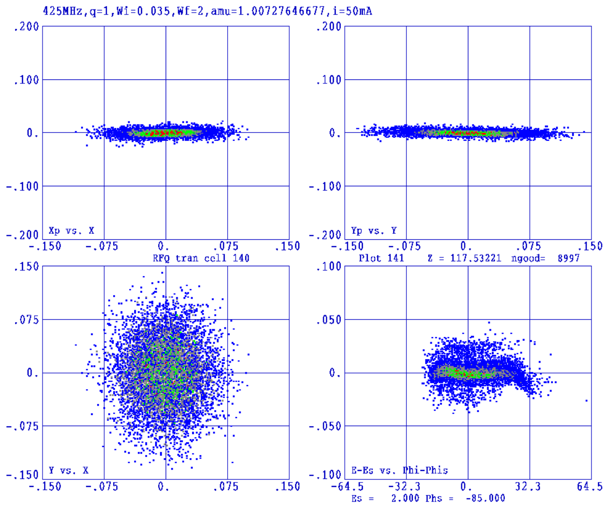

Fig. 4. RFQ output beam emittance in all three planes.

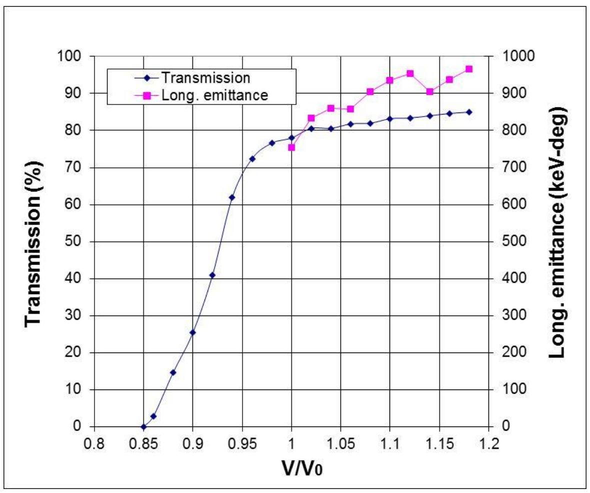

Fig. 5. RFQ output as a function of intervane voltage.

III. BEAM TRANSPORT AND KICKER DESIGN

As described earlier, the operation of this RFQ as an injector for the DWA requires that only a single micropulse be accelerated. This has been accomplished by placing an electrostatic "kicker" in front of the RFQ to deflect the low energy (35 keV) protons from the ion source as they are being focused into the RFQ. This location for the kicker minimizes both the size of the deflection plates and the deflection voltage required. Since the input phase space acceptance of the RFQ is quite sensitive to the angle of the input beam, even a small angular deflection will prevent the beam from being accelerated. This critical performance requirement of the RFQ was exploited to eliminate the unwanted beam from being accelerated using a small deflection at the entrance.

To determine the amount of deflection required to eliminate the beam, the RFQ design code PARMTEQ was used to calculate the beam transmission through the RFQ as a function of angular deflection at the location of the beam kicker. It was assumed that the effective position of the beam deflection was 1 cm in front of the RFQ matching point so that a 0.1 rad deflection would also give a 0.1 cm displacement at the input to the RFQ. Figure 6 shows the calculated beam transmission as a function of deflection in both the X and the Y planes for the case of an ion source output beam current of 35 mA with an emittance of 0.035 π cm-mrad being perfectly matched into the RFQ. However, even when a much larger emittance was assumed the results were quite similar. An input beam current of 35 mA was used because it was found that this would be sufficient to provide the charge required for the operation of the DWA as a proton therapy system. The results of these calculations indicate that an input beam deflection of only 100 mrad will completely prevent the beam from being accelerated in the RFQ.

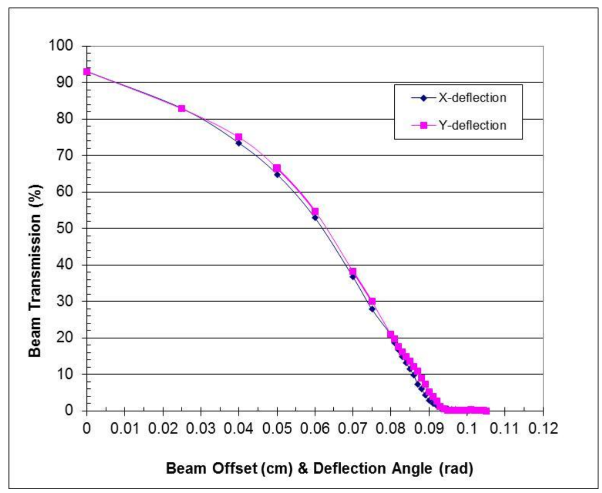

Fig. 6. RFQ beam transmission as a function of the input beam deflection.

An RFQ linac meeting the design specifications for the DWA was procured from AccSys Technology, Inc., and to minimize delivery time, the system purchased included the vendor's standard low energy beam transport (LEBT) consisting of a single einzel lens mounted onto the RFQ input endplate. For DWA injection, the LEBT had to be replaced by one designed to include the electrostatic beam kicker. However, the relatively high 35 mA input current at the low injection energy of 35 keV presented a matching problem in the beam transport between the existing duoplasmatron ion source and the RFQ due to the high space charge, the fixed transport length of the procured system, and the small beam size required in the deflector at the RFQ input. After an extensive beam optics investigation of various matching schemes using the program IGUN,[6] a LEBT design consisting of two decel-accel einzel lenses separated by a single ground electrode was chosen. The ion source extraction electrode and the RFQ input end plate are the other ground planes for the two lenses. The final calculated beam optics for this design is shown in Fig. 7, which also shows the notched area in the located inside the RFQ end plate for the electrostatic kicker electrodes.

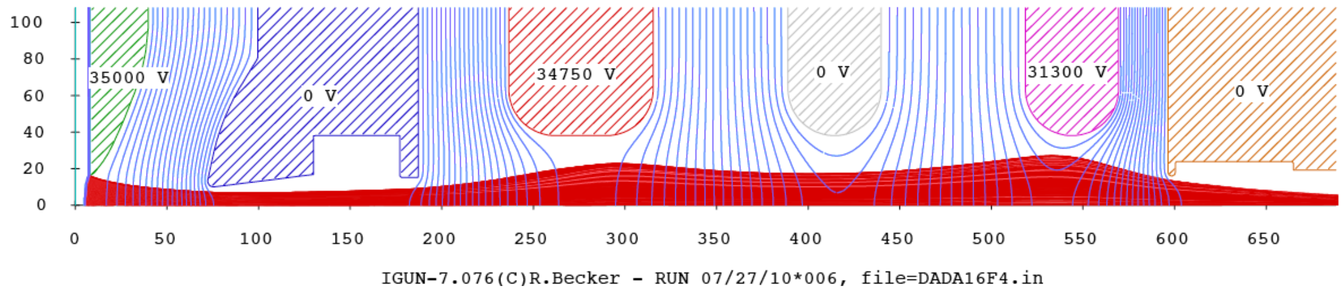

Fig. 7. LEBT beam optics for the DWA injector RFQ (1 unit = 0.25 mm).

The final beam phase space achieved at the RFQ match point with this LEBT is shown in Fig. 8. The RFQ acceptance ellipse is plotted on top of the phase space data, together with an ellipse with the same beam Twiss parameters which just encloses all the trajectories. As can be seen, only a small amount of the beam lies outside the acceptance area when there is no input beam deflection.

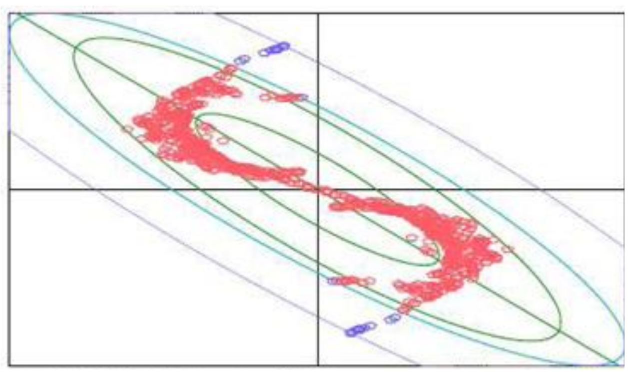

Fig. 8. Calculated input beam emittance from dual lens LEBT. RFQ acceptance ellipse (blue) and total emittance ellipse (magenta) are shown.

The final mechanical layout of the LEBT is shown on the left side of Fig. 9, with the dual einzel lens assembly shown on the right side. As shown in the left side of the figure, the kicker assembly is mounted inside the RFQ cavity end plate. The input proton beam has a diameter of less than 9 mm at the entrance to the kicker plates, with the parallel electrostatic plates separated by 9 mm. The two plates have a width of 20 mm and a length of 12 mm. The total length of the kicker "cavity" in the RFQ endplate is only 16 mm. A dc voltage of only ±7 kV is used on the two plates to deflect the beam out of the RFQ acceptance, with an rf signal of the opposite polarity fed to each plate through a capacitive feedthrough to nullify the deflection and allow the beam into the RFQ acceptance. Computer simulations of the electric fields with the dc deflection and also with the rf pulse canceling it are shown in Fig. 10, along with the input beam particles for each case.

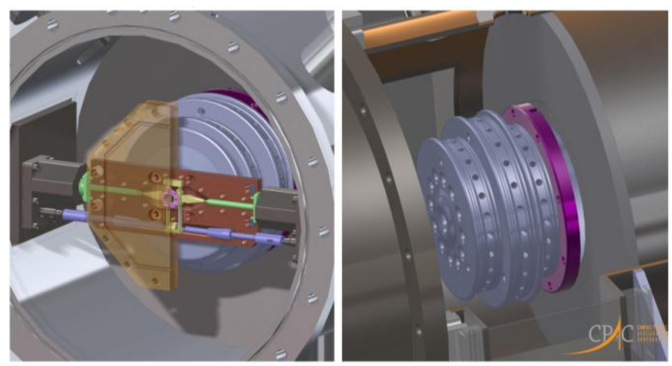

Fig. 9. Final DWA RFQ LEBT assembly.

The problem of synchronizing the kicker voltage pulse with the RFQ input beam, the rf power to the RFQ and the pulsing of the DWA structure is handled by the master timing controller as shown in Fig. 11. This system uses a master timing oscillator to synchronize all subsystems by generating submultiples of the trigger input frequency and by using a pulse slicing technique. The final system has been shown to have a timing jitter of <20 ps. The kicker timing control is a subsystem of the master timing controller that uses precision pulse generators to drive the proton beam into the RFQ and select one or more pulses as required, as indicated in the figure.

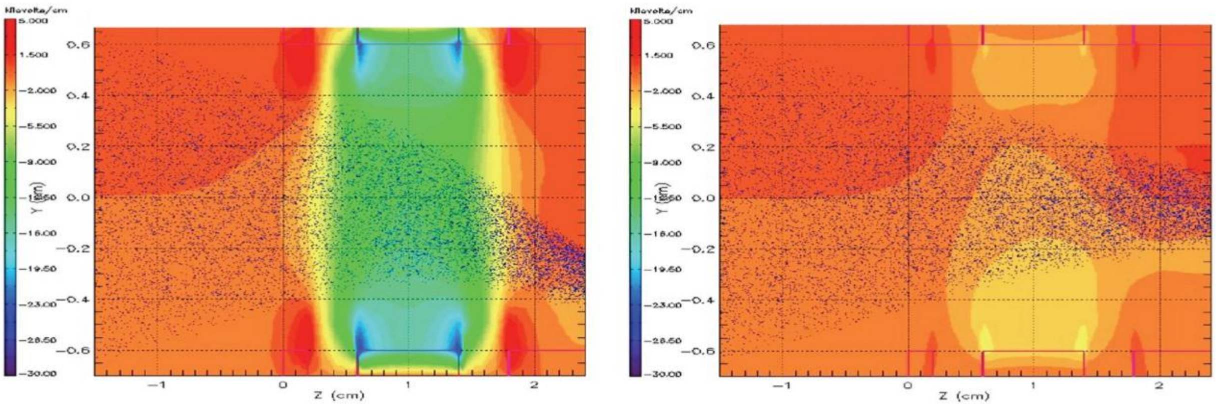

Fig. 10. Computer simulation of the electric fields and beam particles in the kicker.

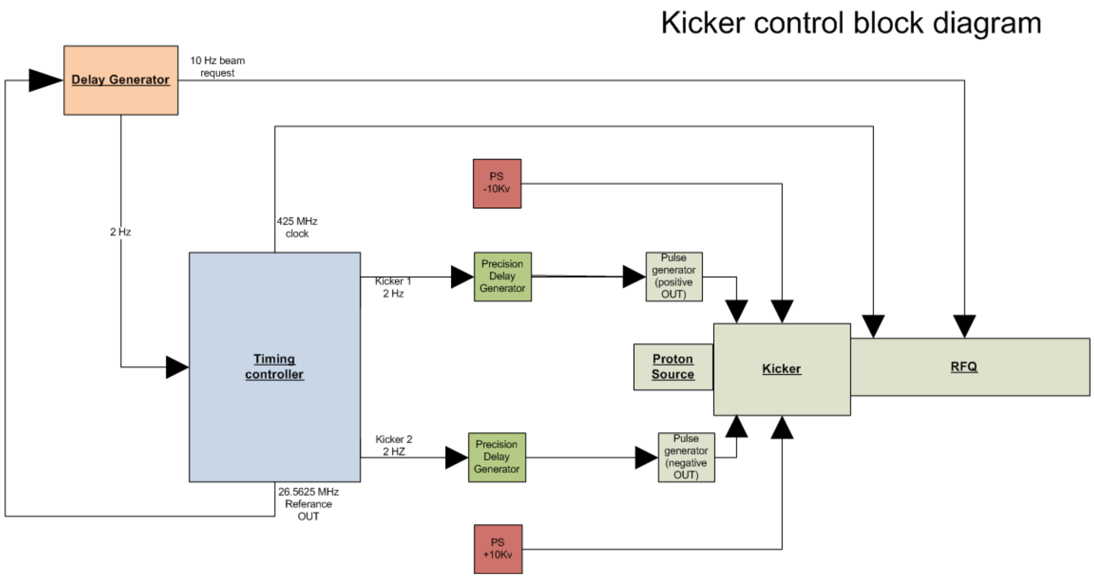

Fig. 11. Timing Schematic for the DWA prototype system.

IV. EXPERIMENTAL RESULTS

The DWA RFQ injector linac is shown in Fig. 12 as viewed from the high energy end. The rf power system on the left is capable of delivering a peak rf power of 350 kW to the RFQ through the coaxial cable seen in the photograph. The entire system, including the ion source and LEBT is mounted on a rigid support frame that has a total length of 1.64 m. For the initial tests of the RFQ deflector, a fast ion collector with a band width of 1 GHz was placed in the output beam of the RFQ approximately 30 cm from the exit, just after the output vacuum valve seen at the right of the photograph.

Fig. 12. Photograph of the DWA RFQ Injector Linac.

The results measured by this ion collector and by a Bergoz fast current transformer coil for a single output pulse from the RFQ are shown in Fig. 13. The green trace is the ion collector output and the magenta trace is the Bergoz coil output. The gold trace is the 425 MHz rf reference signal. The two beam traces have been separated in time for easier display. The proton charge in a single micropulse has been determined to be in excess of 20 pC with an RFQ input beam current of only 22 mA, with only about 1% of this charge in the pre and post rf pulses. This result was achieved with a 2.8 ns pulse applied to the kicker plates. This pulse width can be decreased to a smaller value in the next system and more charge can be captured by decreasing the gap between the plates to reduce the fringe field effects.

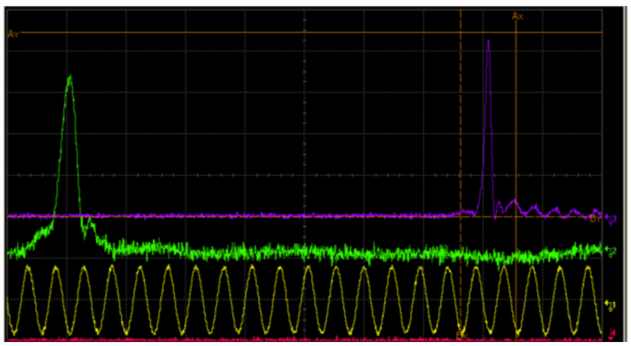

Fig. 13. Measured single micropulse from the DWA RFQ Injector Linac.

The bandwidth of the ion collector does not allow an accurate measurement of the beam pulse time width at this position. Compromises required to maintain the GHz bandwidth of the collector precluded secondary electron suppression, so the charge measurement is calibrated against the percentage of charge relative to a CW fill of known average current and integrated charge from the Bergoz fast current transformer, which give an excellent agreement.

Figure 14 shows the experimental results achieved with a longer kicker voltage pulse to obtain multiple output beam micropulses. This result shows that the micropulses in the middle of the kicker pulse achieve a constant charge and are uniform. This system hence allows the user to select the output pulses required for a particular application.

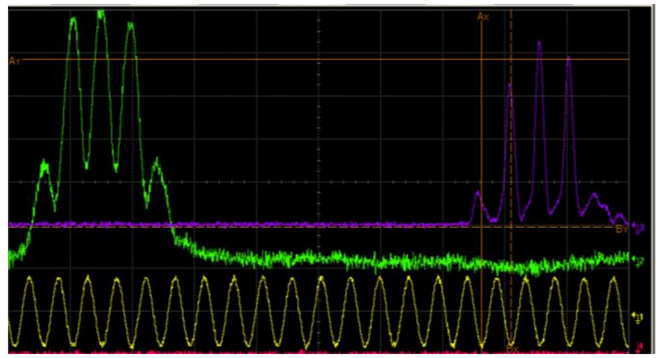

Fig. 14. Selection of multiple micropulses on the DWA RFQ Injector Linac.

Finally, Fig. 15 shows the results of turning the dc deflection voltage off and using the kicker to remove a number of individual micropulses (five shown) from the RFQ macropulse. This result can be extended down to removing a single micropulse (5 ns gap) or up to a longer pulse to remove any number of pulses required. This allows one to create a “notch” in the RFQ output pulse for any time above 5 ns. This kicker design on an RFQ can hence be used to provide a notched input beam for a synchrotron system.

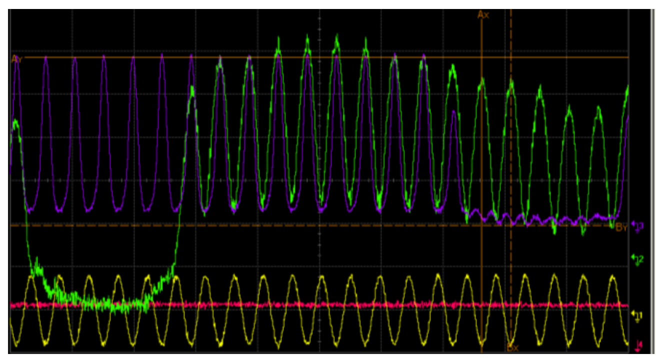

Fig. 15. Operation of the kicker to “notch” the RFQ beam.

V. CONCLUSION

The RFQ linac designed and tested as an injector for the DWA structure has successfully demonstrated that this system can provide the input beam required. This unit has been used to successfully complete the initial demonstration of the DWA structure under development at CPAC and will continue to be used in this development program. In addition, the results from this system will be used for the development of the final clinical unit.

Finally, this RFQ has been used to demonstrate that the input kicker can not only provide any number of individual micro-bunches of ions for use in experimental measurements, but can also be used to create a notch (or notches) in the output beam of an rf linac.

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